Failure Analysis and Preventive Maintenance Framework for Dental Treatment Units in a Specialized Oral Hospital

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Abstract: ***This study analyzes common failure patterns in Dental Treatment Units using 1744 maintenance records from a tertiary oral hospital over 24 months. Failures were classified through subsystem analysis and prioritized using Pareto analysis, identifying five components responsible for most maintenance events. Based on root cause analysis, targeted troubleshooting procedures and a tiered preventive maintenance framework integrating TPM and condition based maintenance were developed. Implementation reduced downtime, lowered maintenance costs, and extended service life. The findings provide practical evidence for optimizing DTUs maintenance management in specialized oral healthcare institutions.***

Keywords: Dental treatment units; preventive maintenance; failure analysis; biomedical equipment management; total productive maintenance; condition- based maintenance

1. Introduction

Dental Treatment Units (DTUs) serve as the primary clinical interface between dental professionals and patients during oral healthcare procedures. In specialized oral hospitals, DTUs are among the most critical medical devices, with utilization rates often exceeding 85% during peak clinical hours.[0] Equipment reliability directly influences clinical workflow efficiency, patient safety, staff working conditions, and institutional revenue. A single DTU failure can disrupt multiple consecutive appointments, causing cascading delays throughout the treatment schedule.

The operational context of DTU maintenance has become increasingly complex in China's specialized oral hospital sector. According to the National Health Commission, over 60% of top-tier tertiary hospitals now operate multiple campuses, with specialized oral hospitals typically maintaining 20–80 DTUs across different clinical departments.[2] This distributed equipment landscape creates unique management challenges, including uneven resource allocation, inconsistent maintenance quality across campuses, fragmented information systems, and coordination inefficiencies in procurement and spare parts management.

Existing literature on medical equipment maintenance has primarily addressed general hospital settings, with limited attention to the distinctive subsystem complexity of DTUs-which integrate hydraulic, pneumatic, electrical, and digital components.[3] Li et al. (2026) identified resource allocation imbalances and maintenance standardization deficits as core challenges in multi-campus hospital equipment management [4], yet did not address the specific failure taxonomy or maintenance protocols required for DTU populations.

This study addresses this specific research gap by conducting a retrospective failure analysis of DTU maintenance records in a tertiary specialized oral hospital, developing subsystem-specific diagnostic and maintenance protocols, and proposing a tiered evidence-based maintenance framework. The four research objectives are: (1) to systematically identify and classify common DTU failure modes by subsystem;(2) to analyze failure root causes and develop structured diagnostic procedures; (3) to develop evidence-based maintenance solutions and optimization strategies; and (4) to validate the proposed framework through measured implementation outcomes over a 12-month pilot period.

2. Literature Review

2.1 Medical Equipment Lifecycle Management

Medical equipment lifecycle management (LCM) encompasses systematic planning, procurement, operation, maintenance, and disposal of medical technology assets throughout their service life.[5] International standards including ISO 13485:2016 (Medical devices quality management systems) and WHO guidance frameworks have established LCM as a core component of healthcare quality assurance and institutional governance.[6] The LCM literature identifies five primary phases: needs assessment and planning, procurement and installation, operational monitoring, maintenance and calibration, and end-of-life disposal.

Data-driven approaches to LCM optimization have gained prominence in recent literature. Recent studies have explored risk-based prioritization models for medical equipment maintenance, demonstrating that preventive maintenance strategies guided by equipment criticality and Risk Priority

Index (RPI) assessment can improve operational reliability and reduce long-term maintenance costs compared with reactive maintenance approaches. However, limited research has specifically addressed dental equipment populations in specialized oral hospitals. [7] Life Cycle Cost Analysis (LCCA) has emerged as a standard evaluation methodology for comparing TCO under different management strategies and justifying capital investments in maintenance infrastructure.[8]

2.2 Dental Treatment Unit Technology and Failure Characteristics

Modern Dental Treatment Units integrate multiple technological subsystems into a unified clinical platform. Core components include: (1) Hydraulic system for seat elevation and positioning; (2) Pneumatic system for handpiece air supply and chip blower functionality; (3) Electrical system including control boards, motors, and position encoders; (4) Water supply system for handpiece cooling and cup filler; and (5) Digital integration for preset positions, chair memory functions, and operator-to-chair communication.

Retrospective research across academic dental clinics has quantified failure patterns at institutional scale. Massoud et al. (2025) analyzed DTU failures recorded over two academic years across six clinical specializations, finding that approximately 70% of failures were attributable to five categories: saliva ejector malfunctions, air delivery system issues, control switch failures, power supply disruptions, and handpiece-related faults.[9] A critical finding was that DTU age showed weak correlation with failure frequency, while clinical workload intensity emerged as a stronger predictor of maintenance needs.

2.3 Preventive Maintenance Strategies

The evolution from reactive to preventive maintenance represents a fundamental paradigm shift in equipment management. Total Productive Maintenance (TPM), originally developed by Nakajima, emphasizes autonomous maintenance by equipment operators combined with planned activities by technical specialists.[10]

Condition-based maintenance (CBM) utilizes real-time monitoring data to trigger interventions only when specific degradation indicators are detected.[11] While CBM requires upfront investment in sensor infrastructure and analytics capabilities, it optimizes maintenance timing and reduces unnecessary interventions. For DTUs, applicable CBM indicators include hydraulic fluid temperature, motor current draw, pneumatic pressure consistency, and electrical component wear patterns.

3. Research Methodology

3.1 Study Setting and Data Collection

This study employs a mixed-methods approach combining retrospective quantitative data analysis with structured qualitative expert interviews. The research was conducted at a specialized oral hospital in Shanghai, a Grade-III tertiary specialized oral hospital operating three geographically distributed campuses with a combined total of 136 Dental Treatment Units across eight clinical departments.

Maintenance records were extracted from the hospital's Computerized Maintenance Management System (CMMS) for a 24-month period (January 2024 to December 2025). Inclusion criteria required that records document: (1) equipment type confirmed as DTU; (2) complete failure symptom description; (3) root cause classification by certified biomedical engineering technician; and (4) resolution time recorded. A total of 1,744 records meeting all criteria were compiled. Records with incomplete subsystem classification or unverifiable resolution data were excluded (n=47, 2.7% of total extracted records).

Each qualifying record captured: failure date and time, equipment identification and campus location, clinical department, failure symptom description, root cause classification, intervention performed, parts replaced, technician assignment, and total resolution time.

3.2 Failure Classification Framework

Failures were classified according to a hierarchical taxonomy developed through a structured consensus process with five biomedical engineering specialists. The primary categories align with the major DTU technological subsystems: hydraulic system failures, pneumatic system failures, electrical system failures, mechanical failures, water supply system failures, and digital/control system failures. To establish content validity, the taxonomy was reviewed against ISO 6875:2023 (Technical specifications for dental treatment units) and refined through two iterative expert review cycles until inter-rater agreement exceeded 90% on a random sample of 100 records.

3.3 Pareto Analysis

Pareto analysis was applied to identify high priority failure categories accounting for the majority of maintenance burden. The Pareto principle (80/20 rule) posits that a small proportion of causes typically drives the majority of problems.[12] Frequency and resolution time data were used to rank failure categories, with cumulative percentage thresholds applied to identify the critical categories for targeted intervention.

3.4 Statistical Validation of Implementation Outcomes

To assess the significance of implementation outcomes, pre- and post-implementation metrics were compared using paired t-tests where normally distributed, and Wilcoxon signed-rank tests for non-parametric measures. Statistical significance was set at $p < 0.05$. Baseline measurements were collected during the six months preceding framework implementation; post-implementation measurements covered the 12-month pilot period.

4. Results and Analysis

4.1 Overall Failure Distribution

The 1,744 maintenance records were distributed across the three campuses as follows: Main Campus (72 DTUs)— 1,075 records (61.6%); Branch Campus 1 (36 DTUs)—429 records (24.6%); Branch Campus 2 (28 DTUs)—240 records (13.8%). Variation in failure rates per DTU across campuses reflects differences in equipment age profiles, clinical workload intensity, and maintenance staffing levels.

4.2 Failure Classification by Subsystem

Table 1 presents the distribution of failures by major subsystem category, ranked by frequency. The six categories with the highest failure incidence collectively account for 73% of all maintenance events, consistent with the Pareto distribution pattern observed in prior research [9].

Table 1: DTU Failure Distribution by Subsystem (January 2024 – December 2025)

Subsystem Category	Failure Count	Percentage	Cumulative %
Saliva Ejector System	356	20.40%	20.40%
Air Delivery System	269	15.40%	35.80%
Control Switches/Buttons	211	12.10%	47.90%
Power Supply Unit	176	10.10%	58.00%
Handpiece Assembly	138	7.90%	65.90%
Hydraulic System	125	7.10%	73.00%
Pneumatic System	111	6.40%	79.40%
Water Supply System	92	5.30%	84.70%
Mechanical Components	84	4.80%	89.50%
Digital/Control Board	67	3.90%	93.40%
Other	115	6.60%	100.00%

4.3 Pareto Analysis Findings

The Pareto analysis confirms that concentrated intervention targeting the top five failure categories (saliva ejector, air delivery system, control switches, power supply, handpiece) could address approximately 65.9% of the total maintenance burden. This finding has direct implications for resource allocation: prioritizing preventive maintenance and spare parts inventory for these categories yields the greatest operational impact.

4.4 Failure Patterns by Equipment Age

Analysis of failure rates by equipment age revealed a non-linear relationship consistent with the "bathtub curve" reliability model. New DTUs (0–2 years) showed elevated early-life failure rates, predominantly involving digital control boards and air delivery system components, likely related to installation and commissioning issues. Failure rates peaked in the 5–7 year age bracket, with hydraulic system degradation and mechanical wear becoming predominant failure modes. Equipment exceeding 10 years showed lower failure rates, likely reflecting survivor bias, with the most problematic units having already been replaced.

4.5 Failure Resolution Time Analysis

Mean time to repair (MTTR) varied significantly by failure category. Electrical system and control board failures exhibited the longest MTTR (mean: 4.2 hours), reflecting diagnostic complexity and parts procurement delays. Control switch replacements (mean: 0.5 hours) and handpiece repairs (mean: 0.8 hours) were typically resolved rapidly. Hydraulic system repairs averaged 2.1 hours, with leak localization and seal replacement as primary activities.

5. Common Problems and Solutions

5.1 Hydraulic System Failures

Common hydraulic system failures include: (a) slow or jerky seat movement caused by air entrainment in hydraulic lines or worn pump components; (b) hydraulic fluid leaks at fittings, seals, or cylinder connections; (c) grinding or whining noises during operation indicating pump or gear wear; (d) complete loss of hydraulic function due to pump failure or fluid reservoir depletion.

Diagnostic Procedures: (1) Visual inspection for fluid beneath equipment; (2) Listen for abnormal sounds during chair operation; (3) Test movement smoothness across full range of motion; (4) Check hydraulic fluid level and condition; (5) Inspect pump operation and pressure readings.

Maintenance Solutions: For air entrainment, perform bleeding by cycling chair through full range 5–10 times; replace worn seals and O-rings at fittings; change hydraulic fluid per manufacturer schedule (typically every 2–3 years); replace pump if pressure falls below specifications; use only manufacturer-specified hydraulic fluid—incorrect viscosity compromises system performance.

5.2 Pneumatic System Failures

Pneumatic system failures manifest as: (a) continuous air leaks during idle state indicating seal or connection failure; (b) reduced handpiece performance due to pressure inconsistencies; (c) intermittent tool operation from moisture contamination or filter blockage; (d) complete loss of air supply from compressor or delivery line failure.

Diagnostic Procedures: (1) Listen for air leaks in idle state; (2) Measure system pressure at chair inlet (normal: 4–6 bar / 60–90 PSI); (3) Check air filter condition and moisture separator; (4) Test individual handpiece performance; (5) Inspect airline connections for damage.

Maintenance Solutions: Daily drainage of compressor receiver tank and chair-side moisture separators; monthly inspection and replacement of air filters; annual pressure calibration and safety valve testing; install desiccant air dryers in high-humidity environments; maintain compressor per manufacturer schedule.

5.3 Electrical System Failures

Electrical failures include: (a) intermittent control response caused by loose connectors or failing switches; (b) complete power loss from power supply unit failure or circuit protection trip; (c) chair position memory malfunction due to encoder or control board faults; (d) safety interlock failures compromising emergency stop functionality.

Diagnostic Procedures: (1) Verify power supply connectivity and circuit breaker status; (2) Inspect electrical connections for looseness or corrosion; (3) Test control panel response to input commands; (4) Check encoder feedback signals; (5) Verify safety circuit continuity.

Maintenance Solutions: Keep liquid sources away from electrical panels; check all connectors monthly; replace failing switches proactively before complete failure; maintain spare control boards for critical equipment; never bypass safety interlocks; assign all electrical work to qualified personnel.

5.4 Saliva Ejector System Failures

As the most frequent failure category, saliva ejector (SE) system problems include: (a) weak or intermittent suction due to blockage or motor wear; (b) complete loss of suction from motor failure or air intake leaks; (c) noisy operation indicating bearing wear or debris ingestion; (d) water backup from line blockages [10].

Diagnostic Procedures: (1) Test suction at ejector tip with water; (2) Inspect suction lines for kinks or blockages; (3) Check separator and collection container; (4) Measure vacuum pump performance; (5) Listen for abnormal motor sounds.

Maintenance Solutions: Daily flush with clean water to prevent biofilm accumulation; weekly inspection and cleaning of suction tips and lines; monthly check of separator and seals; quarterly motor performance assessment; replace worn tips and damaged tubing promptly; implement single-use barriers to reduce contamination.

5.5 Handpiece and Air Delivery System Failures

Handpiece failures encompass: (a) reduced rotation speed or power from turbine wear; (b) excessive vibration indicating bearing damage; (c) air/water spray malfunctions; (d) quick-connect fitting failures [10].

Diagnostic Procedures: (1) Run handpiece unloaded to assess sound and vibration; (2) Test air and water spray functions; (3) Inspect turbine chuck for wear; (4) Check drive air pressure; (5) Examine fiber optic light transmission.

Maintenance Solutions: Establish handpiece rotation testing as a daily startup procedure; follow manufacturer lubrication schedules (typically after each use); implement chuck inspection and replacement program (every 6–12 months); train clinical staff on proper handling; maintain adequate handpiece inventory for rotation; record turbine run hours to predict replacement timing.

6. Proposed Maintenance Framework

6.1Tiered Preventive Maintenance Strategy

Based on the failure analysis findings, we propose a tiered preventive maintenance framework that aligns maintenance intensity with failure criticality and clinical impact. The framework comprises three tiers: (1) Autonomous Maintenance (AM) performed by clinical staff as part of daily operations; (2) Planned Preventive Maintenance (PPM) conducted by biomedical engineering technicians on scheduled intervals; and (3) Condition-Based Maintenance (CBM) triggered by real-time monitoring indicators or performance degradation signals.

6.2 Daily Autonomous Maintenance Protocol

Clinical staff should perform the following checks at the start of each operating day: (1) visual inspection for physical damage, fluid leaks, or unusual conditions; (2) test all DTU movements through full range for smoothness; (3) verify safety stop function operates correctly; (4) check suction performance at saliva ejector; (5) confirm handpiece air/water spray functions; (6) clean surfaces with appropriate disinfectants. These checks require approximately 5 minutes per unit and can identify issues before they impact clinical operations.

6.3 Scheduled Preventive Maintenance

Table 2 outlines recommended preventive maintenance intervals based on failure data patterns.

Table 2: Preventive Maintenance Schedule for Dental Treatment Units (DTUs)

Frequency	Maintenance Activities
Daily	Safety function test; suction performance check; visual inspection
Weekly	Air filter drainage; handpiece lubrication verification; surface cleaning
Monthly	Air filter inspection/replacement; mechanical fastener check; control function test
Quarterly	Hydraulic fluid level check; pneumatic pressure calibration; electrical connection inspection
Semi-Annual	Full subsystem inspection; seal replacement program; performance baseline testing
Annual	Comprehensive system overhaul; component lifecycle assessment; spare parts inventory review

6.4 Spare Parts Management

Effective maintenance requires strategic spare parts inventory aligned with observed failure patterns. Based on Pareto analysis findings, institutions should prioritize stock levels for: (1) saliva ejector components (tips, seals, tubing)- highest consumption; (2) control switches and buttons- frequent failure; (3) handpiece repair kits and bearings; (4) hydraulic seals and O-rings; (5) air filters and separators; (6) control board assemblies for critical units. Bin stocking and par-level management should be implemented to balance availability against inventory costs.

6.5 Implementation Outcomes

The proposed framework was implemented across all three hospital campuses over a 12-month pilot period. Pre- and post-implementation comparisons of key performance metrics are presented in Table 3. All primary outcomes were statistically significant ($p < 0.05$).

Table 3: Framework Implementation Outcomes (12-Month Pilot, $p < 0.05$ for all metrics)

Performance Metric	Baseline	Post-Implementation	Change
Unplanned Downtime (hrs/month)	28.6	18.8	−34.2%
Mean Time to Repair (hours)	2.4	1.9	−20.8%
Preventive Maintenance Compliance	52%	87%	67.30%
Average Equipment Age at Replacement	8.2 years	10.5 years	+2.3 years
Annual Maintenance Cost per DTU	¥8,450	¥6,030	−28.6%
Patient Appointment Disruption Rate	3.20%	1.40%	−56.3%

7. Discussion

The concentration of failures in five subsystem categories- accounting for 65.9% of all maintenance events- confirms and extends the Pareto distribution previously reported by Massoud.[9] The dominance of saliva ejector failures (20.4%) reflects high usage intensity and contamination exposure inherent to this component in oral clinical environments. The combined contribution of handpiece and air delivery system failures (23.3%) underscores the critical importance of maintaining pneumatic interface components that directly affect clinical procedure execution.

The weak correlation between equipment age and failure frequency has important implications for maintenance planning beyond this institution. Rather than applying uniform age-based replacement schedules, institutions should prioritize condition-based assessment and workload-adjusted maintenance intervals. The observed peak failure rate at 5–7 years warrants enhanced monitoring and potentially accelerated component replacement at this age bracket, informing procurement planning.

The 67.3% improvement in preventive maintenance compliance demonstrates the effectiveness of structured scheduling combined with accountability mechanisms. A shift from reactive firefighting to planned intervention scheduling was the primary driver of improved labor utilization, which in turn contributed to the 28.6% reduction in annual maintenance costs. The 2.3-year extension in average equipment service life offers substantial capital deferral benefits, supporting the long-term financial case for maintenance investment.

7.1 Limitations

This study has several limitations. First, the single-institution study context may limit generalizability to hospitals with different equipment profiles, clinical specializations, or geographic conditions. Second, the 12-month pilot period demonstrates initial improvements but cannot establish long-term outcome sustainability. Third, the study did not incorporate advanced predictive maintenance technologies (IoT sensors, machine learning algorithms) that may offer further optimization potential. Future research should explore these advanced approaches and validate the framework across diverse institutional contexts.

8. Conclusion

This study identified major DTU failure patterns across five high-priority subsystem categories and developed an evidence-based tiered preventive maintenance framework that demonstrably improved equipment reliability, reduced downtime, and lowered maintenance costs. The findings support a strategic shift from reactive maintenance toward structured, risk-informed maintenance management in specialized oral healthcare institutions. Equipment age alone is a poor predictor of DTU failure; workload-adjusted and condition-based approaches are more effective scheduling criteria.

The proposed framework- integrating autonomous maintenance by clinical staff, scheduled planned preventive maintenance, and condition-based interventions- offers practical, scalable guidance for DTU maintenance management. Implementation requires coordinated commitment from clinical and technical staff, investment in preventive scheduling systems, and strategic spare parts management aligned with Pareto-derived failure priorities. The framework may support broader application in other specialized hospital settings managing complex multi-subsystem clinical equipment.

References

[1] Ishimaru, M., Taira, K., Zaitsu, T., Inoue, Y., Kino, S., Takahashi, H., & Tamiya, N. (2022). Characteristics of hospitals employing dentists, and utilization of dental care services for hospitalized patients in Japan: a nationwide cross-sectional study. International Journal of Environmental Research and Public Health, 19(11), 6448.

[2] Zhu, X., & Yan, X. (2023). A rapid expansion of hospitals: The adaptation of multi-campus hospitals under the Chinese healthcare system. Frontiers in Health Services, 3, 1226355.

[3] Lin, Z., Kang, J., Wei, Y., & Zou, B. (2024). Maintenance management strategies for medical equipment in healthcare institutions: a review. BME Horizon, 2(3), 135-135.

[4] Li, J. Z., Lao, Y., Shen, Y., Bin-Nashwan, S. A., Jiang, H., Jiang, Q., & Kuang, X. (2026). Integrative operations management framework for large-scale tertiary hospitals: a multidisciplinary empirical analysis. Journal of Health Organization and Management, 40(9), 243-265.

[5] Bos, G., & Joiner, T. (2025). ISO 13485: 2016—Medical Devices—Quality Management Systems—Requirements for Regulatory Purposes. In Medical Regulatory Affairs (pp. 167-188). Jenny Stanford Publishing.

[6] World Health Organization. (2017). WHO global model regulatory framework for medical devices including in vitro diagnostic medical devices.

[7] Jamshidi, A., Rahimi, S. A., Ait-Kadi, D., & Ruiz, A. (2015). A comprehensive fuzzy risk-based maintenance framework for prioritization of medical devices. Applied Soft Computing, 32, 322-334.

[8] Altaf, M., Alaloul, W. S., Musarat, M. A., & Qureshi, A. H. (2023). Life cycle cost analysis (LCCA) of construction projects: sustainability perspective. Environment, Development and Sustainability, 25(11), 12071-12118.

[9] Massoud, S., Ismaiel, E., & Al Kayal, A. (2025). Retrospective analysis of dental chair failures and usage patterns in academic dental clinics. Scientific Reports, 15(1), 42065.

[10] Nakajima, S. (1988). Introduction to TPM: total productive maintenance. (Translation). Productivity Press, Inc., 1988, 129.

[11] Jardine, A. K., Lin, D., & Banjevic, D. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mechanical systems and signal processing, 20(7), 1483-1510.

[12] Tague, N. R. (2023). The quality toolbox. Quality Press.

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